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FINAL REPORT

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Least Squares Computations in Science and Engineering

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February 1994

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Table of Contents

Least Squares Computations in Science and Engineering

Abstract

Least squares computations constitute a fundamental tool in science and engineering. The reason is that they play a critical role in fitting numerical models to real world observations. This AFOSR supported research effort has been concerned with the design and testing of new algorithms for least squares computations and optimization in science and engineering. The objectives were to mathematically develop, test, and analyze fast numerical algorithms for the efficient solution to problems on modern high performance computers. The focus of this project was the application of scientific computing technology in the area of signal and image processing. Very many problems lead to over determined systems of linear or nonlinear equations that are often solved by least squares or related optimization methods. Generally, the problems are accompanied by constraints, such as bound constraints, and the observations are corrupted by noise. The project has involved the application of scientific computing in the area of computational linear and nonlinear least squares methods with particular applications in image and signal processing, where recovering images is often an ill-posed inverse problem. Additional work included control computations associated with adaptive optics. General topic areas that were considered in this research include:

- Fast algorithms for *adaptive estimation and filtering, along with sensitivity analysis*, with applications in signal processing.
- Image reconstruction algorithms for *3-D computed tomography*, in the verification and inspection of aerospace structures.
- Fast *deconvolution methods using the FFT*, including regularization techniques, for certain structured ill-posed inverse problems arising in 2-D image restoration.
- Matrix *trace maximization applications for control methods*, with applications to adaptive optics systems.

Some of these research projects have been investigated in collaboration with researchers at Phillips Air Force Laboratory, Kirkland AFB.

Key Words: constrained least squares, adaptive filtering, adaptive optics, deconvolution, image restoration, parallel algorithms, trace maximization, inverse problems, FFT.

1. Introduction

This AFOSR supported research effort has been concerned with the design and testing of new algorithms for least squares computations and optimization in science and engineering. The objectives were to mathematically develop, test, and analyze fast numerical algorithms for the efficient solution to scientific problems on modern high performance computers. The focus of this project was application of scientific computing technology in the area of signal and image processing.

Special emphasis is given to applications of potential interest to the U.S. Air Force. In particular, the principle investigator visited and interacted with researchers in the Lasers and Imaging Division at the Phillips Air Force Laboratory at Kirkland AFB on three occasions (See Section 3). He also spent the first six months of 1992 visiting the Institute for Mathematics and Its Applications at the University of Minnesota. The visit enabled him to interact and collaborate with several researchers from universities, industry, and government laboratories from around the country. During the three years of the grant, two Ph.D. students were directed and one is in progress (See Section 4), twenty-four papers have been completed or are currently in progress (See Section 5), and twenty-eight technical presentations have been given on this AFOSR sponsored research (See Section 6). We turn now to a brief summary of the research objectives.

Part of our research effort was in the area of time-recursive least squares. One of the main efforts here has been directed toward determining stability, conditioning, performance, and architectural implementation of fast adaptive algorithms for *FFT-based time recursive methods*. Such fast algorithms are receiving ever increasing attention due to the expanding availability of commercial multiprocessors and special purpose computers. The results of this effort is widely applicable to the next generation of signal processing systems in business, defense, and engineering. This effort has involved interaction with researchers in closed-loop active noise (vibration) control at Phillips Air Force Laboratory, Kirkland AFB.

In the area of large scale least squares computations, with applications, e.g., to *image reconstruction and restoration*, we have been concerned with the development of effective FFT-based preconditioners for linear and non-linear conjugate gradient iterations. Special attention was given to deconvolution problems, which lead to block Toeplitz and related least squares problems. These problems arise in a variety of application areas, especially reconstruction and restoration methods in image processing. An important problem that has been addressed here is that of image restoration of the object from a degraded and noisy image measurement. This effort has also involved interaction with researchers at Phillips Air Force Laboratory at Kirkland AFB.

Another direction of our work involves the design and testing of scalable parallel algorithms for signal and image processing on massively parallel computers. This work is in conjunction with personnel at General Electric CRD in Schnectady, NY and at Cray Research in Minneapolis, MN. The principle investigator is working on these problems with my former Ph.D. student, William Harrod, at Cray Research. Technology transfer to industry for our algorithms and software is an important aspect of this work.

Adaptive optics control systems form the subject of considerable recent investigation. This project relates to a very interesting problem posed by Dr. Brent Ellerbroek during one of the principle investigator's visits to Phillips Laboratory, Kirkland AFB. Specially designed deformable mirrors operating in a closed-loop adaptive optics system can partially compensate for the effects of atmospheric turbulence. The systems detect the atmospheric distortions using either a natural guide star (point) image or a guide star artificially generated from the back scatter of a laser generated beacon. A wave front sensor measures the optical distortions that can then be partially nullified by deforming a flexible mirror in the telescope. The problem reduces to trace maximization computations. The optimal control system may be used in conjunction with the Department of Defense's largest optical telescope, currently being installed at Kirkland Air Force Base's Starfire Optical Range.

General topic areas investigated in this research included:

- Fast algorithms for *adaptive estimation and filtering, along with sensitivity analysis*, with applications in signal processing.
- Image reconstruction algorithms for *3-D computed tomography*, in the verification and inspection of aerospace structures.
- Fast *deconvolution methods using the FFT*, including regularization techniques, for certain structured ill-posed inverse problems arising in 2-D image restoration.
- Matrix *trace maximization applications for control methods*, with applications to adaptive optics systems.

Specific research accomplishments and activities are outlined in the following sections.

2. Research Accomplishments

Experience in mathematical analysis and scientific computing is being used to attack some difficult computational problems, arising especially in multidimensional signal and image processing. The principle investigator has work on the applied aspects of this research with some colleagues and former Ph.D. students in industrial laboratories, including, Boeing, Cray Research, and General Electric, as well as with some researchers with the Air Force Phillips Laboratory, Kirkland AFB.

♦ **FFT-Based Recursive Least Squares Computations with Applications to Adaptive Filtering.** In 1986, Gilbert Strang addressed the question of whether iterative methods can compete with direct methods for solving symmetric positive definite Toeplitz systems of linear equations. The answer has turned out to be an unqualified yes. Strang proposed the use of circulant matrices to precondition conjugate gradient iterations for Toeplitz systems. The reason this approach is competitive with direct methods is clear. The use of circulant preconditioners for these problems allows the use of Fourier transforms throughout the computations, and these FFT-based iterations are not only numerically efficient, but also highly parallelizable.

Numerous articles have extended the Strang idea to more general Toeplitz systems, and several types of circulant preconditioners have been suggested. Recently, we have developed FFT-based preconditioners for solving Toeplitz least squares problems, where applications include such important signal processing problems as active noise cancellation, seismic deconvolution, data compression, and image restoration. The purpose of part of this work is to address the question of whether iterative methods can compete with direct methods for recursively solving least squares problems in an adaptive signal processing environment.

Adaptive finite impulse response (FIR) filters are used extensively in many signal processing and control applications: for instance, in system identification, equalization of telephone channels, spectrum analysis, noise cancellation, echo cancellation and in linear predictive coding. The main concerns in the design of adaptive filtering algorithms are their convergence performance and their computational requirements. These concerns are especially important when the filters are used in real-time signal processing applications or the sizes of the filters are very large (as is the case in acoustic echo or active noise cancellation problems.) We are considering both recursive least squares (RLS) computations and least mean squares (LMS) methods. For the LMS case, we have proposed a new FFT-based LSM-Newton algorithm. Preliminary numerical results show that the performance of the algorithm is good in the sense of stability and convergence. Also, the complexity of the algorithm for **n** filter parameters is only O(**n** log **n**) operations per each adaptive time step and the algorithm itself is highly parallelizable. These attractive features could lead to the use of the algorithm in diverse adaptive filtering applications. (See publication 21.)

Recursive least squares problems arise naturally in autoregressive (AR) and AR moving average (ARMA) computations in systems identification, and in general FIR filtering. Thus far we have reduced the classical complexity number for recursive least squares computations from $O(\mathbf{n}^2)$ to $O(\mathbf{n} \log \mathbf{n})$, by using the FFT, where **n** is the number of filter parameters (See publications 2, 5, 6, 7, 8, 12, 13, 16, 19 and 21). We are now attempting to reduce the complexity of our transform-based schemes to $O(\mathbf{n})$, by incorporating wavelet approximations. Possible applications include adaptive noise cancellation or vibration control work at Phillips Laboratory.

♦ **Scalable Parallel Algorithms for Image Analysis and Reconstruction**. This is part of some 3-way collaboration between myself, working under this AFOSR grant, and personnel at the General Electric CRD at Schnectady, NY, together with a former Ph.D. student, William Harrod, at Cray Research in Minneapolis. Dr. Harrod is in charge of designing applications software for Cray's new massively parallel computer, their Tourus connection 3-dimensional architecture (T3D).

This collaborative project performed by the private industry and university team is establishing a scalable parallel programming environment for message-passing distributed memory architectures for applications in multidimensional signal processing and image analysis. The regularities of the data structures, the homogeneous nature of the calculations, and the number of applications of multidimensional signal processing and image analysis provide an unparalleled opportunity to exploit the potential of modern massively parallel computers. We are concentrating on developing portable, scalable, parallel algorithms for processing and analyzing very large multidimensional data sets with well-defined neighborhood relationships between data elements. Examples of such data sets include X-ray digital radiographs, X-ray computerized tomographs, synthetic aperture radar, visual/infrared camera, laser radar, towed arrays, and high-resolution satellite images. The algorithms will be implemented on a selection of target architectures, included mesh connected, hypercube, heterogeneous, and re configurable arrays. One such platform includes the Cray MPP super computer T3D, made available by the principle investigator's former Ph.D. student William Harrod at Cray Research.

Another topic in this overall project is the application of parallel algorithms to image reconstruction on massively parallel architectures. The 3-D image reconstruction approach we are considering with General Electric is based on the following:

- Data collection by cone beam scanning. The use of fan or parallel beam scanning is too slow for the data collection in the applications we have in mind.
- Conversion of the cone beam projection data to Radon data, consisting of planar integrals.
- 3-D Radon transform inversion. This particular method consists of two steps, each of which involves a 2-dimensional filtered back projection algorithm.

Some feel that cone beam x-ray computerized tomography (CT) inspection systems will form the basis for the next generation of CT inspection technology for both industrial and military uses. However, the cone beam approach is still too computationally intensive for many applications even on advanced parallel architectures, since for practical problems rapid inspection of large numbers of objects with high voxel dimensions is needed; thus the interest in investigating the possible use of scalable parallel algorithms for MPP architectures here, in order to reduce the on-line inspection time. Contacts through General Electric are have also been made with researchers at the Wright-Patterson Laboratory, concerning our help with their project of periodic non-destructive inspection of Air Force equipment parts and materials. (See publications 10, 17 and 20.)

♦ **Deconvolution Methods for Image Restoration.** Here, the work involves application of our new FFT-based preconditioning schemes for Toeplitz and related least squares computations to image deblurring problems. Our novel approach is to precondition in the frequency domain, while iterating in the spatial domain for high performance. It is important to recover the information in a blurred image; in remote sensing, details about the photographed terrain should be clarified; in medical imaging, the diagnosis is based on the clarity of the x-ray radiographs taken; in space activities, images transmitted to earth by unmanned or manned spacecraft need to be analyzed. Our work on preconditioning techniques can be applied directly to image restoration computations for 2-D signals, where the **point spread function** (PSF), represented by $\mathbf{h}(\mathbf{x},\mathbf{y})$, is spatially invariant, and thus leads to a block Toeplitz operator. Such situations arise in ground based astronomical imaging tests at the Starfire Optical Range, Kirkland AFB. Equations relating the observed and blurred image to the true image can be written algebraically in matrix equation form as

$$\mathbf{g} = \mathbf{Hf} + \eta,$$

where $\mathbf{g}$ represents the blurred image, $\mathbf{H}$ represents the discretized PSF, $\mathbf{f}$ is the true image, and η represents the noise process in recording the image. Practical problems are typically ill-posed and therefore very sensitive to model uncertainty and to noise. We are interacting with personnel in the Lasers and Imaging Division at Phillips Air Force Laboratory on this project. (See Section 3 and publications 10, 14, 17, 18, and 24.)

♦ **An Optimization Problem in Adaptive Optics Control.** This work was not part of the original proposal, but came about when an interesting research problem was posed during a visit by the principle investigator to the Phillips Laboratory in February 1993, by Dr. Brent Ellerbroek. The optimization application involves the solution of a trace maximization problem, associated with orthogonal transformations of a set of mirror matrices for closed loop system in adaptive optics. This adaptive optics work relates to the adaptive control of a set of very fast-acting deformable mirrors whose surface shapes can change rapidly to correct for optical distortions caused by the atmosphere. Matrix computations often play an important role in aero-optics applications for astronomical and aero-optics imaging. The problem we have considered involves the optimal real-time control of a very fast-acting deformable mirror designed for atmospheric turbulence compensation. The surface shape of this mirrors must change rapidly to correct for time-varying optical distortions caused by the atmosphere. The sensor measurements used to compute these corrections are noisy, and for each spatial mode of the distortion there is an optimal control bandwidth balancing residual errors induced by sensor noise and servo lag. One formulation of this problem yields a functional f(U) to be maximized over unitary matrices U, where U defines the basis of orthonormal control modes to be used, and characterizes adaptive optics performance when all deformable mirror degrees of freedom are controlled at a common bandwidth. Numerical experiments are undertaken, using some practical data from an astronomical telescope system at the Kirkland AFB, Starfire Optical Range. The problem is being approached using eigenanalysis (See Section 3, and publications 22 and 23).

3. Interaction with Phillips AF Laboratory

The focus of this interaction with Phillips Laboratory at Kirkland AFB, which was supported by the grant AFOSR-91-0163, is the application of scientific computing in the area of computational methods and analysis in image and signal processing. General topic areas that have been considered in aspect of the AFOSR research project include:

1. Matrix *trace maximization applications to control* of deformable mirrors for closed loop adaptive optics systems, in conjunction with Brent Ellerbroek at Phillips Laboratory.

2. Fast *deconvolution methods* using FFT and fast wavelet based conjugate gradient iterations, including regularization techniques for ill-posed inverse problems in image restoration, in conjunction with Richard Carreras and Brent Ellerbroek at Phillips.

These projects are briefly reviewed below. Each topic relates to imaging through atmospheric turbulence.

Astronomers and other scientists have long sought to overcome the degradation of astronomical image quality caused by the effects of atmospheric turbulence. These effects are in part due to the mixing of warm and cold air layers. The resulting twinkling of the stars and other effects are the main limitations of ground-based imaging for both scientific and defense purposes. As pointed out vividly in a January 1994 National Geographic Magazine article, *New Eyes on the Universe*, exciting technological breakthroughs are rapidly coming to the aid of scientists attempting to deblur astronomical images.

The improvement in ground-based image quality is now generally attempted in two stages. The first stage occurs as the observed image is initially formed. Specially designed deformable mirrors operating in a closed-loop adaptive optics system can partially compensate for the effects of atmospheric turbulence. The systems detect the distortions using either a natural guide star (point) image or a guide star artificially generated from the back scatter of a laser generated beacon. A wave front sensor measures the optical distortions that can then be partially nullified by deforming a flexible mirror in the telescope. To be effective, these corrections have to be performed at near real-time speed. Adaptive optics control systems form the subject of considerable recent investigation. Project # 1 relates to a very interesting problem posed by Dr. Ellerbroek during one of the principle investigator's visits to Phillips Laboratory. The problem relates to the adaptive control of a set of very fast-acting deformable mirrors whose surface shapes can change rapidly to correct for optical distortions caused by the atmosphere. By developing a mathematical model of the closed loop adaptive optics system, the problem of estimating the optimal mirror control parameter vector **c(t)** at time **t** has been reduced by Dr. Ellerbroek to the solution of a matrix trace maximization problem, associated with orthogonal transformations of set of mirror matrices $M_1, M_2, \ldots, M_p$, for the closed loop system. In conjunction with C. Van Loan and N. Pitsianis at Cornell University, the problem has been approached using eigenanalysis. Two joint papers with Dr. Ellerbroek will follow from this study. The optimal control system may be used in conjunction with the Department of Defense's largest optical telescope, currently being installed at Kirkland Air Force Base's Starfire Optical Range. (See publications 22 and 23.)

The second stage of compensating for the effects of atmospheric turbulence generally occurs off-line, and consists of the image processing step of restoration. An image partially corrected by the adaptive optics procedure discussed above can generally be enhanced further by off-line computer image restoration. Here, large-scale computations, again using either a natural guide star (point) image or a guide star artificially generated from the back scatter of a laser generated beacon, are used to deconvolve the blurring effects of atmospheric turbulence. In this regard, removing a linear, shift-invariant blur from a signal or image can be accomplished by inverse or Wiener filtering, or by an iterative least squares deblurring procedure. Because of the ill-posed characteristics of the deconvolution problem, in the presence of noise, direct filtering methods often yield poor results; but, on the other hand, iterative methods often suffer from slow convergence at high spatial frequencies. To accelerate convergence, we use the preconditioned conjugate gradient iterative algorithm. A new approximate inverse Toeplitz preconditioner is used to further increase the rate of convergence. Test results are reported for a ground-based astronomical imaging problem in publication 24. In particular, Project #2 is concerned with deconvolution methods for image restoration. Here, the work involves application of our new FFT-based preconditioning schemes for constrained nonlinear least squares computations to image deblurring problems. Our novel approach is to precondition in the frequency domain, while iterating with nonlinear conjugate gradients in the spatial domain for high performance. This facilitates application of constraints such as non negativity and finite support. Fast throughput is achieved by using the FFT throughout the computations. This work on preconditioning techniques can be applied directly to image restoration computations for 2-D signals, where the point spread function (PSF) is spatially invariant. Here the blurred image formation process is modeled as:

$$g(x,y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h(x-\alpha,y-\beta)\, f(\alpha,\beta)\, d\alpha\, d\beta \; + \; \eta(x,y).$$

Equations relating the blurred image to the true image can thus be written in discrete matrix form as $\mathbf{g} = \mathbf{Hf} + \eta$, where **g** represents the blurred image, **H** represents the discretized PSF, **f** is the true image, and η represents the noise process in recording the image. In actual practice, *no matrices need to be formed to execute the algorithm.* Image degradation occurs in a variety of imaging systems; including industrial radiography, non-destructive evaluation, medical imaging, remote sensing, aerial reconnaissance, ground-based imaging, and space-based imaging. Practical problems are typically ill-posed and therefore very sensitive to model uncertainty and to noise. Our computations are being performed on a vector-parallel Cray Y-MP. For the important case where the point spread function is not spatially invariant due to the small size of the isoplanatic angle in atmospheric imaging systems, the use of wavelet-based preconditioners is also being investigated. (See publication 20.)

Interaction on this image restoration work has been made with researchers at Phillips Laboratory at Kirkland AFB. In particular, we are testing our schemes on data used at Kirkland from an ensemble of photographs taken by the Air Force of satellites from the ground looking up. The blurring is caused by atmospheric turbulence. This area of research may lead to important advances in high speed computations in restoration of ground-based images. We are coordinating our work with Brent Ellerbroek and with Richard Carreras, who are kindly providing us with the real imaging data at Phillips Laboratory on this project. In particular, the figure below illustrates the fast convergence of our FFT-based preconditioned conjugate gradient method for data provided to us from Phillips Laboratory. (The figure will appear in publication 24.)

4. Graduate Students

The following Ph.D. students have worked with or are currently working with the principal investigator as part of this research grant. Two of the students graduated at the end of 1991, and a third student has begun her Ph.D. studies in Computer Science at North Carolina State University under the direction of the principal investigator.

• **James Nagy**. Dr. Nagy completed his Ph.D. in Mathematics with a minor in Electrical and Computer Engineering in December 1991, under the direction of the principal investigator. He was supported for one summer under this grant. His dissertation topic at NC State University involved Toeplitz and related least squares computations in signal and image processing, identification, estimation and control. He was awarded a Post Doctoral position with the Institute for Mathematics and Applications, University of Minnesota, for the academic year 1991-92. He accepted a faculty position in Mathematics at Southern Methodist University beginning August 1992.

• **William Ferng**. Dr. Ferng completed his Ph.D. in Mathematics with a minor in Computer Science in December 1991, under the direction of the principal investigator. He was supported for one summer under this grant. He did his undergraduate work in Electrical and Computer Engineering in Taiwan. William has considerable parallel processing and super computing experience. His dissertation topic at NC State University involved parallel Lanczos algorithms applied to problems in optimization and engineering. He was awarded a Post Doctoral position with the U.S. Army High Performance Computing Research Center in Minneapolis, for the academic years 1991-92 and 1992-93. He accepted a position in Computer Science at a Taiwan university in August 1993.

• **Sherri Braxton**. Ms. Braxton is a very bright Afro-American U. S. student who received her undergraduate degree with a joint Mathematics and Computer Science major at Wake Forest University in May 1992. Her participation in this AFOSR research project began with her work the summer of 1992 on ill-posed inverse problems in image processing. She has a fellowship in the Ph.D. program in Computer Science at NC State University, where the principle investigator is directing her work.

5. Technical Publications

1. *Block cyclic SOR for Markov chains with p-cyclic infinitesimal generator*, **Lin. Alg. Applications** Special Issue on Iterative Methods, vols. 154-156 (1991), 145-224. (This 79 page paper is joint with K. Kontovasilis and W. J. Stewart).

2. *Adaptive Lanczos methods for recursive condition estimation*, **Numerical Algorithms**, 1 (1991), 1-20. (with William R. Ferng and Gene H. Golub).

3. *Order-reducing conjugate gradients vs block AOR for constrained least squares problems*, **Lin. Alg. Applications** 154-156 (1991), 23-44. (by former Ph.D. student AF Major Douglas James, and part of his dissertation work supported by a previous AFOSR grant).

4. *Some fast Toeplitz least squares algorithms*, **Proc. SPIE Symposium on Signal Proc. Algs., Architectures, and Implementations**, 1566 (1991), 35-46. (with J. Nagy).

5. *An inverse factorization algorithm for linear prediction*, **Lin. Alg. Applications** 172 (1992), 169-195 (with J. Nagy).

6. *Fast adaptive condition estimation*, **SIAM J. Matrix Anal. and Applic.**, 13 (1992), 274-291 (with D. Pierce).

7. *A parallel implementation of the inverse QR adaptive filter*, **Computers and Electrical Engineering** 18 (1992) , 291-300 (with S. Alexander and A. Ghirinikar).

8. *Tracking the condition number for RLS in signal processing*, **Mathematics of Control, Signals, and Systems** 5 (1992), 23-39 (with D. Pierce).

9. *A fast algorithm for linear prediction*, in **Recent Advances in Mathematical Theory of Systems, Control, Networks and Signal Processing II**, Ed. by H. Kimura and S. Kodama, MTA Press Tokyo (1992), 15-21 (with J. Nagy).

10. *Block circulant preconditioners for 2-D deconvolution problems*, **Proc. SPIE Symposium on Advanced Signal Processing Algorithms, Architectures, and Implement.**, 1770 (1992), 60-71. (with R. Chan and J. Nagy).

11. *Analysis of p-cyclic iterations for Markov chains*, to appear in **Linear Algebra, Markov Chains, and Queuing Models**, Ed. by C. Meyer and R. Plemmons, IMA Volumes in Mathematics and Its Applications, Springer Verlag 48 (1993), 111-124 (with A. Hadjidimos).

12. *Block RLS using row Householder reflections*, **Lin. Alg. and Applications**, 188 (1993), 31-62. (with A. Bojanczyk and J. Nagy).

13. *Fast recursive least squares using the FFT*, **IMA Tech. Rept. 982**, Univ. Minnesota (1992), **Proc. Conf. on Mathematics of Signal Processing**, Warwick, England, Oxford Press, 1993.

14. *Preconditioned iterative regularization methods for ill-posed problems*, **Numerical Linear Algebra and Scientific Computing**, de Gruyter Press, Berlin, (1993), 141-163. (with M. Hanke and J. Nagy).

15. Iterative image restoration using FFT-based preconditioners, **Proc. 30th Allerton Conf. on Comm., Control and Computing,** Allerton, IL, 1993. (with J. Nagy).

16. *FFT-based RLS in Signal Processing*, **ICASSP- 93, Minneapolis, MN, IEEE Press,** Vol. III (1993), 571-574.

17. *FFT-based preconditioners for Toeplitz-block least squares*, **SIAM J. on Numerical Analysis,** 30 (1993), 1740-1768. (with R. Chan and J. Nagy).

18. *Circulant preconditioned Toeplitz least squares iterations*, **SIAM J. Matrix Analysis and Applic.** 15 (1994), 80-97. (with R. Chan and J. Nagy).

19. *Fast RLS adaptive filtering by FFT-based conjugate gradient iterations*, to appear in the **SIAM J. on Scientific Computing.** (with M. Ng).

20. *Image Restoration using Fast Fourier and Wavelet Transforms*, invited paper at the **International Symposium on Substance Identification Technologies,** Conference on Signal and Image Processing for Detection Systems, Innsbruck, Austria, October (1993). (To be published by the European Optical Society, 1994).

21. *Fast LMS-Newton adaptive filtering by FFT-based conjugate gradient iterations*, submitted to the **IEEE Trans.. on Signal Processing,** 1994. (with M. Ng).

22. *Optimizing closed loop adaptive optics performance using multiple control bandwidths*, submitted to the **J. Optical Soc. Amer.,** 1994. (with B. Ellerbroek, C. Van Loan and N. Pitsianis).

23. *A Trace Maximization Problem in Adaptive Optics*, in preparation, 1994. (with B. Ellerbroek, C. Van Loan and N. Pitsianis).

24. *Fast restoration of atmospherically blurred images*, in preparation, 1994. (with J. Nagy and T. Torgersen).

6. Invited Research Presentations

1. **Parallel Algorithms for Signal and Image Processing**, Plenary Talk, *SIAM Southeast Regional Conference*, Cullowhee, NC, April 1991.

2. **Non Negativity and Convergent Iterations**, Invited Talk, *International Linear Algebra Society Conference*, DeKalb, IL, May 1991.

3. **Toeplitz Least Squares Preconditioners**, Invited Talk, *Southeas ·a Mathematics Society Conference*, Hong Kong, June 1991.

4. **A Systolic Array for Recursive Least Squares Computations**, Department of Computer Sci., Zhongshan (Sun Yat-Sen) Univ., Guangzhou, P.R. China, June 1991.

5. **An Inverse Factorization Algorithm for Linear Prediction**, *Inter. Confer. on Mathematics of Networks and Systems and Control*, Kobe, Japan, June 1991.

6. **Extended SOR Iterations**, *NSF Conference on Multigrid Methods for Partial Differential Equations*, Washington, DC, June 1991.

7. **Fast Algorithms for Toeplitz Least Squares Computations**, *SPIE Symposium on Advanced Signal Processing Algorithms, Architec., and Impl.*, San Diego, July, 1991.

8. **Dynamic Condition Estimation**, Organizer of Mini symposium, *SIAM Confer. on Applied Linear Algebra*, Minneapolis, MN, September 1991 (co-author of 2 invited talks).

9. **Scalable Parallel Algorithms for Signal and Image Processing**, Colloquium, *North Carolina Super Computing Center*, Research Triangle Park, NC, November (1991)

10. **Matrix Iterative Analysis for Markov Chains**, *IMA Workshop on Solving Markov Chains*, Minneapolis, MN, January 1992 (also, co-organizer of the Workshop).

11. **FFT-Based Toeplitz Least Squares Problems**, Invited Talk, *IMA Workshop on Sparse and Structured Matrix Problems*, Minneapolis, MN, February 1992.

12. **Block Toeplitz Iterations on a Cray Y-MP**, Invited Talk, *Permian Basin Super Computing Conference*, Odessa, TX, March, 1992.

13. **Block Toeplitz Least Squares Iterations**, Colloquium, *NC State Univ.*, April 1992.

14. **Preconditioned Iterative Least Squares FIR System Identification**, Invited Talk, *IMA Workshop on Signal Processing*, Minneapolis, MN, April 1992.

15. **Large-Scale Block Toeplitz Least Squares Iterations**, Invited Talk, *International Domain Decomposition for PDE Conference*, Como, Italy, June, 1992.

16. **Building FFT-Based Preconditioners in Signal Processing**, Invited Talk, *Workshop on Mathematics in Signal Processing*, Stoors, CT, July, 1992.

17. **Block Circulant Preconditioners for 2-D Deconvolution**, *SPIE Symposium on Advanced Signal Processing Algorithms, Architectures, and Implementations*, San Diego, CA, July, 1992 (also, co-organizer of Symposium).

18. **FFT-Based RLS in Signal Processing**, Invited Talk, *IMACS International Symposium on Mathematical Modeling and Scientific Computing*, Bangalore, India, Dec., 1992.

19. **Generalized inverses in Signal Processing**, Invited Talk, *Workshop on Generalized Matrix Inverses*, Indian Statistical Institute, New Delhi, India, Dec., 1992.

20. **Toeplitz Matrices and Iterative Least Squares Estimation**, *Short Course*, given at the Indian Statistical Institute, New Delhi, India, Dec., 1992.

21. **Fast Recursive Least Squares using the FFT**, *Third IMA Conf. on Mathematics in Signal Processing*, Warwick, England, Dec., 1992.

22. **FFT-Based RLS in Signal Processing**, *IEEE Inter. Conf. on Acoustics, Speech and Sig. Processing*, Minneapolis, MN, April, 1993.

23. **Fast Recursive Least Squares for Noise Cancellation**, *Colloquium Presentation*, Phillips Air Force Laboratory, June, 1993.

24. **Preconditioners for Least Squares Iterations**, Plenary Talk, *Householder Conference on Numerical Analysis*, UCLA Conf. Center, CA, June 1993.

25. **Structured Matrix Computations in Signal Processing**, Invited Talk at the *SIAM Tutorial on Numerical Meth. in Control, Signal and Image Proc.*, Seattle, August, 1993.

26. **Building Preconditioners for Toeplitz and Related Systems**, *SIAM Conf. on Lin. Alg. in Control, Signal and Image Processing*, Seattle, WA, August, 1993.

27. **Image Restoration using Fast Fourier and Wavelet Transforms**, Invited Talk, *International Symposium on Substance Identification Technologies, Signal and Image Processing for Detection Systems*, Innsbruck, Austria, October, 1993.

28. **An Optimization Problem in Adaptive Optics**, Invited Plenary Talk, *Lanczos International Conference on Computational Mathematics and Physics*, Raleigh, NC, December, 1993.